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The Prospects for Finite Element Analysis Methods for Structural Qualification

NORTH ATLANTIC TREATY ORGANIZATION

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No.736

THE PROSPECTS FOR FINITE ELEMENT ANALYSIS METHODS FOR STRUCTURAL QUALIFICATION

Papers presented at the 61st Meeting of the Structures and Materials Panel of AGARD
in Oberammergau, Germany, 8—13 September 1985.

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CONTENTS

STRUCTURAL QUALIFICATION BY FINITE ELEMENT ANALYSIS

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(Originally presented at the 61st Meeting of the Structures and Materials Panel,
September, 1985)

SUMMARY

The report discusses the effect of the emergence of the finite element package as a design and validation facility which has become more accessible as computer hardware has improved and software become friendlier. In the aircraft industry the traditional relationship between analysis and test has been for the former to establish load paths and local stress levels, which are then fed into separate analysis or data sheets, or component tests, to predict strength, life or other failure modes. The full scale test validates the whole process. Now that finite element (linear) analysis is used to predict local stress levels, there will be a temptation to use it to predict failure modes - which are invariably nonlinear. The next step could be to omit the experimental test completely, even for first production types. The commercial pressures already exist.

Topics discussed are the crucial roles of quality and reliability in existing finite element systems and in the user organisations; the growing number of bodies and advisory groups who are looking at this problem both nationally and internationally. NATO could adopt an early role in establishing standards which may become part of future legal clauses on product liability.

1. INTRODUCTION

Structural tests, whether for Military or Civil aircraft are expensive, and if they can in any way be avoided or reduced, then manufacturers may have the edge over competitors who choose to conduct a full test programme. Even if the cost of experimental testing was not continually increasing,the alternative analytical routes to validation are decreasing in real terms as the CAD/CAM interface is integrated with finite element analysis systems. In Europe the various separate authorities are likely to control the degree of experimental testing that is required. In the United States the Air Force also is likely to follow this practice. However, the United States Army tends to follow the manufacturers lead and we may therefore expect commercial pressures to reduce expensive testing for helicopters for example.

It has been the practice to call for structural tests (static, fatigue and dynamic) on all new aircraft to validate the design strength and the analytical predictions for stress, deformations, or life. The loading will be an envelope of design cases to produce the worst structural response at the factored ultimate design loads in the case of static strength. The test will verify the analytically predicted load paths and reveal also the local strength or failure mode and whether this was predicted accurately. Similar revelations will emerge from the fatigue tests. However, if the aircraft is subsequently modified for a new role or customer, it is not generally considered necessary to repeat a full UDL test if the original validation was satisfactory.

Frequently it is found that in-service load monitoring leads to a revision of the original load spectrum. Again, an analytical reappraisal of reserve factors is considered adequate. Examples where drastic revisions have not been retested include the British Aerospace HS125, the Westland WG30 (which has a completely different fuselage from the original Lynx) and the R.A.F. tanker version of the Tristar. Of course the dangers of missing a change in failure mode are potentially more serious for military high-performance aircraft where service loading up to 80% of UDL is not uncommon. It is less likely in civil aircraft or military transporters, but there are also the dangers of changing the fatigue life.

2. THEORETICAL ANALYSIS AND EXPERIMENTAL TESTING

Taking the somewhat simplified view it has long been the practice to use theoretical analysis to estimate the load paths and stress levels in aircraft structures. Airworthiness authorities will require validation for a considerable number of design cases and a theoretical prediction of load paths will therefore be necessary even to demonstrate that the experimental test and loading spectrum are correctly simulating the worst design cases. Having predicted local stress levels the next stage is an estimate of allowable stress, whether this be a proof requirement, a buckling stress, a residual strength, life, or aeroelastic criterion. These estimates themselves may be analytical, empirical, based on test experience, or a composite data sheet based on all three routes. In the design stage the estimates of allowable stress can be approximate, but the check-stressing phase can involve further

expensive testing if the failure modes are in doubt.

In checking this whole procedure as a proof of structural integrity, the airworthiness authorities would certify the competence of the design organisation to undertake both analysis and test. They would likely lay down standards for the testing rigs, machines and procedures. The tests may also be witnessed, but in any case documented evidence would be required of the analysis and tests, and a type record produced of Reserve Factors for each aircraft variant. The aim of authorities is to minimise errors in experimental testing, in simulation of in-service loading, and in analytical procedures used to predict safety margins. The emergence of computer-based methods and commercial finite element programs may force a change in this proven procedure.

3. FINITE ELEMENT ANALYSIS

The finite element method is now the most widely used structural analysis technique. As the cost, accessibility, and power of computer hardware has improved, so has the number of finite element packages increased. In-house finite element programs were pioneered in the aircraft industry and their limitations understood, but the authors have probably now moved on, and the tendency is to use commercial packages as black boxes. The most significant developments lately have been the improvements in pre-processors which have cut dramatically the effort needed to create a finite element model in the first instance so that finite element analysis may now be used ab initio for both the project design phase and for the final detailed check stress. At least one site in the United Kingdom has found it cheaper and less prone to data error to generate a finite element model for the complete aircraft in the design phase and then be prepared to modify both geometry and sizes as the design is refined. Thus finite element systems are now an integral pat of the design and redesign cycle, and it is these systems which will predict the load paths through the structure and select the worst loading actions and consequent stress fields for all parts of the structure.

At this stage the only new sources of error, not present in the past, will be in the skill of the finite element modeller and the reliability of the finite element system. The analysis is invariably linear at this juncture. However, because of the relative cheapness and flexibility of computer-based analysis, the pressures already exist for using finite element systems to predict local strength and failure modes. These modes may involve material failure or yield, crack propagation, thinwalled plate buckling, etc. and so are invariably nonlinear. A nonlinear analysis even of local features is expensive, particularly if it is used to interact with the global model and redistribute the load paths. If a structure is designed to be fail-safe or damage-tolerant then this redistribution should be followed. Nevertheless, finite element predictions of failure, using a local refined model, are becoming potentially cheaper than a series of tests to cover a large parameter range of sizes, shapes and materials. Clearly the accuracy of computed predictions of failure is still open to question when the process may be a three-dimensional nonlinear phenomenon, and the detailed material and geometrical modelling may be complex. Particularly in composites. There is also the requirement that the analyst must successfully pick the likely modes of failure when creating a numerical model capable of simulating that failure. No such prior judgement is necessary of course in speculating where a test failure will originate. Tests usually spring surprises.

These issues are addressed separately.

4. RELIABILITY OF FINITE ELEMENT SYSTEMS

The certifying airworthiness authorities may conceivably be presented simply with a computer output of tables or contour maps etc., and have to assess the accuracy of the information. Apart from the competence of the design organisation in using finite element analysis, the quality of any commercial system should be assessed or verified by a suitable authority. This requirement has already been made mandatory by several U.K. Government authorities in the fields of nuclear reactor technology, marine and railway structures and vehicles, and by Lloyds. In principle the same evidence of reliability expected of testing machines should be expected of software. There are several aspects of modern finite element packages which are pertinent.

(i) The quality assurance of software. Unfortunately this can mean almost anything, and it frequently simply ensures that updates of the system still leave it capable of producing the same answers as before the updates. The prototype may still be faulty.

(ii) The pedigree of elements. Many elements are heuristic, and several systems deploy 'tuning' measures to correct known limitations or deficiencies in their elements. These numerical tricks are not always disclosed in the public domain.

(iii) The robustness of the system and its pre/post-processors. Users are coming to expect a friendly system which will flag warning signs when the analysis is suspect due to conditioning problems or a poorly prescribed structural model or supports. Complex aerospace models may be particularly at risk if substructures from several sites are brought together and errors in data interfacing can be made.

Pre-processors should indicate unacceptable mesh distortions, artificial cracks and voids, and other element incompatibilities. Post-processors should diagnose poor results and not just smooth out discontinuities. Systems are therefore now acquiring error-estimate procedures and adaptive refinements which may be automated without further user instructions.

(iv) There are suspect features in most finite element systems which are not available for examination since developers will never wish to hand over source programs which could be useful to competitors.

These problems are being actively pursued in some countries. In the United Kingdom the government-sponsored National Agency for Finite Element Methods and Standards (NAFEMS) [1] is preparing a series of tests, procedures and benchmarks for assessing finite element systems. Information is being collected and published on system performance, registered users, educational courses and aids. NAFEMS has published Guidelines to Good Practice, a Finite Element Primer, and more guides are planned. Members of NAFEMS have indicated that comparative system performance indicators are a most valuable impartial aid. They have also asked for more guidelines to be published and two further ones on Dynamics and Nonlinear Analysis are being compiled under contract. In the United States the A.I.A.A. and now A.S.M.E., A.S.C.E. are attempting similar initiatives and tests, but they are relying on developers to fund most of the costs, and these American initiatives seem likely to degenerate into a battle-ground for developers to produce conflicting evidence. In Europe several industrial/governmental sectors are preparing tests and minimum standards, particularly in the sensitive field of nuclear technology. This role could be adopted by co-ordinating bodies like the EEC or NATO. NAFEMS itself has over 200 subscribing corporate members, more than 30% of whom are outside the United Kingdom, and a clear need has been identified for recognised standards and unprejudiced assessment.

5. USER COMPETENCE

If the perfect finite element system existed, with all the geometrical and numerical checks and diagnostics necessary to alert the unwary, the structure still has to be idealised. Because the computational model can be extremely sophisticated, the opportunities exist to model features which would have been unthinkable in the days of longhand analysis. This of course may introduce further opportunities for error, and indeed the finite element analyst may be totally unsuited by training to spot absurdities that the traditional stressman would intuitively recognise. There is therefore considerable interest being shown in the use of expert systems as a front-end to pre-processors and as an aid to modelling. The investment costs are high in building in the accumulated wisdom from past designs and configurations, and the current expert systems are not particularly suited to this form of knowledge store. Nevertheless the exercise has been started at British Aerospace (Warton) and this, together with parallel developments in the States, should prove the reliability of this strategy.

The aerospace industry rightly considers that it has a duty to be competent and that it has the expertise to use finite element systems with skill. However, the airworthiness authorities might consider that this competence should be proven. NAFEMS is now preparing a definition of user competence which places the onus on the organisation to meet minimum standards for engineers to have the right training, experience and knowledge of the finite element system it uses. Competence to successfully run the NAFEMS tests may be one criteria, experience in reconciling finite element analysis with selected experimental tests may be another.

6. FINITE ELEMENT PREDICTION OF STRENGTH

Much in-house experience in assessing strength is to be found in manufacturers' design manuals. They contain a wealth of experience built on analysis and on test. Unfortunately they become dated as design practices or materials change. New testing programmes are time-consuming and expensive and a computer-based alternative looks attractive. Special purpose programmes already exist, for example for predicting buckling in stiffened panels [3].

A joint S.B.A.C./M.o.D. [2] committee in the United Kingdom is currently looking into the problems of analysis by finite elements, and is finding that most sites in the airframe industry are making tentative examinations into the use of finite element models in predicting failure where a test would conventionally be used. Such examples might be the effect of stress concentrations in complex three-dimensional components such as forgings and castings, lugs, diffusion members, post-buckled panels, crack initiation and stopping. Initial attempts in these nonlinear problems have been partially successful (outright failures are rarely reported) and work is continuing (finite element models for predicting failure in various three-dimensional joints are being evaluated at British Aerospace, Woodford, for example). Having validated such numerical tests the rewards are manifest. It should be possible to examine alternative designs at a fraction of the cost of a series of tests. Of course there are several areas of static and fatigue failure where component tests will always be inevitable, for example environmental degradation in both metals and in composites.

7. FAILURE IN COMPOSITES

Enthusiasm for composites seems cyclic, and the quoted reasons for choosing them tend to change from "better performance" to "cheaper production". Nevertheless, they do seem to be holding their promise against intense competition from lithium-aluminium alloys. Problems of environmental degradation and impact damage are being overcome in the new fibres and materials, but there is still a residual fear that a weak link will be revealed when the prototype is first tested. Many composite failures are precipitated by delamination due to "through-thickness" stresses in situations where the designer had assumed a simple two-dimensional stress field. Such three-dimensional behaviour can arise due to holes, joints, other discontinuities, or simple 'edge effects'. In metals these effects may be ignored but a weak composite matrix will unmercifully exploit such stress fields.

This particular point is raised here to illustrate the hazards waiting for the finite element analyst. No-one can envisage deploying three-dimensional finite element schemes throughout a composite structure. Yet if we wait for experience to be accumulated industry will have to keep its empirical "knock-down factors" and make composites look uncompetitive.

8. FUTURE DEVELOPMENTS

Already mentioned has been the need to make finite element systems user-friendly, robust, and capable of self-checking errors by various diagnostic routes. Possibly the next far-reaching development is the integration of finite element analyses into a complete CAD/CAM cycle including automated optimum design of the structure. It does not make sense for any organisation to exploit CAD techniques to generate geometrical information for design and production and then to deploy further teams of engineers to prepare a finite element model. A big cost saving will arise from an international standard for neutral formats so that one geometrical database can be used for everything including analysis. Thus the total design cycle is now becoming more automated. Already several special-purpose CAD/CAM systems have a finite element analysis package embedded within them, and naturally they are being used by engineers or designers who have little knowledge of finite elements and of the dangers inherent in any approximate analysis. We cannot simply say that it is dangerous to use finite element systems as if they were black boxes, they <u>will</u> eventually be used in this fashion and we therefore have to ensure that the black box <u>is</u> of a proven standard.

9. CONCLUSIONS

There is much, partly justified, scepticism in the use of computational models, yet finite element capabilities continue to improve. Two questions are therefore posed:

(1) Can we rely entirely on finite element analysis to predict load paths and stress fields in complete strucures ?

(2) CAn we trust finite element models to predict local allowable stresses ?

If the answers are no, then the finite element system will become a design tool embedded in the CAD/CAM cycle, and experimental tests will always be obligatory. Only the manufacturer will suffer if the computer-aided design fails to pass the test.

If the answer is yes, to (1) or (2), then there must be safeguards:

(1) Finite element systems have to be accurate and robust,and proof should be provided of quality assurance to certifying authorities.

(2) Modelling must be skillful and automated where possible.

(3) Firms should demonstrate that they have the organisation to cope with the complex models and data bases.

(4) The results of computer analysis have to be presented to certifying authorities in a readily understandable manner. Confidence limits should be disclosed.

Finally, the aerospace industry has much expertise in the field of analysis and validation and should be ideally placed to assess the competence of any finite element system to find stresses and predict failure. A valuable exercise would be for several organisations to undertake an analysis of, say, a standard NATO test specimen using current finite element systems. The advantage of a common benchmark over an existing design would be that no single organisation would have a prejudiced reputation to protect. The benchmark could be relatively simple and cheap even though it should embody features known to be important in aerospace. It should be possible also to organise a relatively cheap experimental test in parallel.

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Application of Nonlinear FE/FD - Methods for Support of Structural Tests

by

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SUMMARY

The aim of the paper is to show the beneficial interaction of numerical analysis and experimental investigation in the field of nonlinear structural response. This is illustrated by applications of the DYSMAS-code, developed at IABG for the computation of highly nonlinear wave propagation and material flow in the short time range, consisting of a 3D-Lagrangian code, a 3D-Eulerian code and a coupling module. Difficulties in comparison of numerical and experimental results are sketched in a symbolic manner.

INTRODUCTION

To bring forward the knowledge about nonlinear structural response and to establish proper prediction methods it has been proven to be useful to applicate analytical and experimental tools in combination. However, one must know the nature of experimental investigation and numerical simulation to avoid errors in application and interpretation in both methods.

1. NATURE OF EXPERIMENT AND NUMERICAL SIMULATION

Fig. 1 illustrates the nature of experiment and numerical simulation.

The experiment runs in the "real world". It is influenced by all initial and boundary conditions, known and unknown. Mostly, essential parts of the physical event take place in a black box, and only a part of them can be observed via the used measurement techniques, visible as a picture of the physical process, influenced by the measurement itself, and not as the "real physical event". As result, experiments always give "real world results" of course.

The numerical simulation runs in a "physical world". It takes only into account those initial- and boundary conditions, necessary for the physical principles covered by the theory of the numerical model. Mathematical methods are used for a numerical solution as an "essential result". The advantage of numerical simulation is to get full information about the physical event in dependency of space and time. Prerequisite for accurate modelling is the implementation of all physical principles essential for the problem and proper and stable solution techniques which have to be verified.

2. ROLE OF NUMERICAL SIMULATION

Due to the nature of numerical simulation typical advantages in its application are:

- better understanding of the physical event
- variation of properties
- simulation of initial and boundary conditions, in an ideal and independent manner

As a consequence application of numerical simulation is a helpful support for structural tests in the field of

- planning the experimental set up and measurement techniques e. g. by information about the necessary sensitivity and location of the gages and the forces to be taken by the supports.
- reducing the number of experiments in the case of optimization e. g. by numerical trend analysis
- evaluation of experiments e. g. with interpretation by numerical verification of the test.

3. EXAMPLES

The three manners of supporting structural tests are illustrated subsequently by typical examples:

Planning the experimental set up:

In problems of fluid structure interaction the structural loading is unknown and in most cases nearly impossible to estimate. For the experimental investigation of the effect of an underwater detonation to a ship structure the information about the best position and the necessary sensitivity of the gages is most important, especially at the immense costs

of such an experiment. The factility of numerical simulation is illustrated by a coupled Eulerian-Lagrangian computation considering the effect of an underwater detonation to a test bucket. Fig. 2 shows the FE-mesh of the bucket structure within the Eulerian grid mapping the surrounding water. Two different states of the growing gas bubble and the vertical motion of the bucket, caused by the detonation, are shown in Fig. 3. The measured and calculated displacement transient of the bottom of the bucket are compared in Fig. 4.

Reducing number of experiments

For the automotive industry, safety of a car's passenger cabin in a crash accident gains increasing importance. Especially for prototypes, crash-tests are very expensive, and the results are often late for a design optimization. So it's very attractive to simulate crash-testing on the computer. Fig. 5 shows the front half of a car structure without engine and wheels in the undeformed and deformed state after a numerical drop test with an impact velocity of 13 m/s. Fig. 6 shows the comparison of measured and calculated accelerations at a plate, which was fixed at the rear of the structure.

Evaluation of experiments

For the design of armor configurations, the knowledge about details of material failure during piercing processes is a necessary information. Fig. 7 shows a target plate and the recovered projectile and plug after the penetration. In Fig. 8 the penetration process as a result of numerical simulation is to be seen. As an essential result of the numerical simulation, Fig. 9 shows the shear strain distribution during the first phase of penetration, where the plug is separated from the residual plate material. The contours show a propagating area of maximum shear strain initiating the failure mechanism followed by plug separation, which is also modelled in the simulation by debonding finite elements.

4. DIFFICULTIES IN COMPARISON

As mentioned above concerning the nature of experiment and numerical simulation, none of both methods yield a real image of the physical event. The picture one can get is more or less influenced by the lens "measurement technique" or "solution algorithms".

The best case to be achieved is illustrated in Fig. 10. The picture is scaled but similar due to the optical property of the lens, and a part of the real image is univisible as it is shadowed.

The worse case is shown in Fig. 11. An improper or wrong measurement or solution technique creates a result, which is completely different from the real event. This can be caused e. g. by resonance of gage frequencies or numerical instabilities.

The worst case however is demonstrated in Fig. 12. A miraculous, supernatural lens makes the real image visible. It's always suspicious, if measurement or numerical solution discovers all aspects of a physical event, in spite of its natural limitations.

In general if both methods, experimental and numerical investigation are used in combination, not the same type of error will occure and the results will be different. In this case each expert will try to convince the other one of the reliability of the own result and to discover errors in the other one's. Such discussions are a real chance to discover errors and to come out with the right result, which is sometimes even different of the first results of both.

CONCLUSION

In the very complex field of nonlinear structural response, highly sophisticated numerical simulation can be a very beneficial support for structural tests. Moreover, experimental and numerical methods are really two equivalent brothers, and they fare well by joining together.

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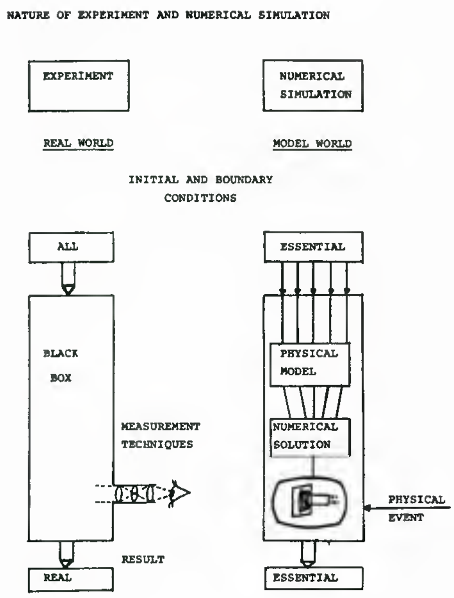

Fig. 1 Nature of experiment and numerical simulation

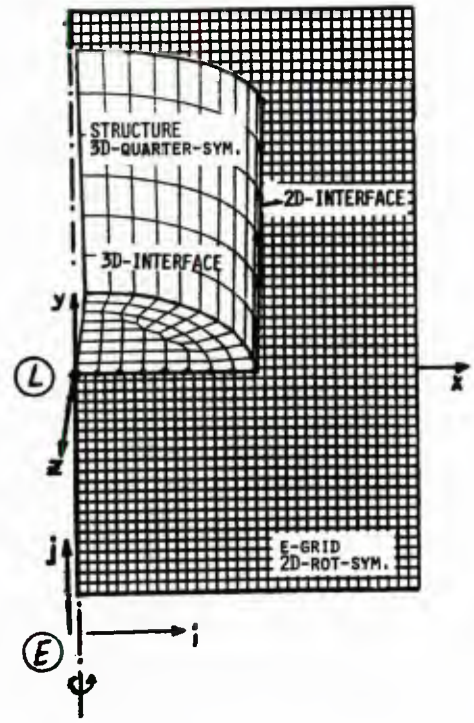

Fig 2 Test bucket, discretisation coupling 3D-Lagrangian and 2D-Eulerian grid [1]

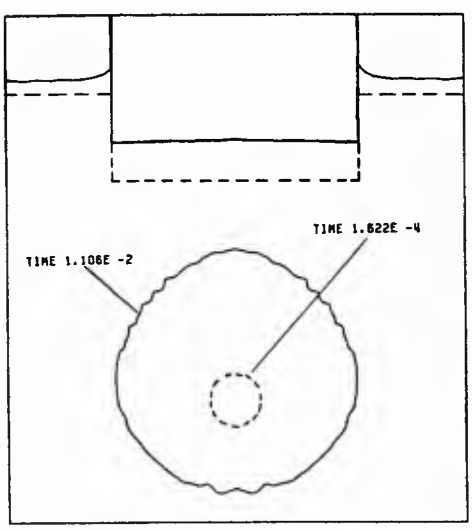

Fig. 3 Underwater detonation, expanding gas bubble and accelerated structure [1]

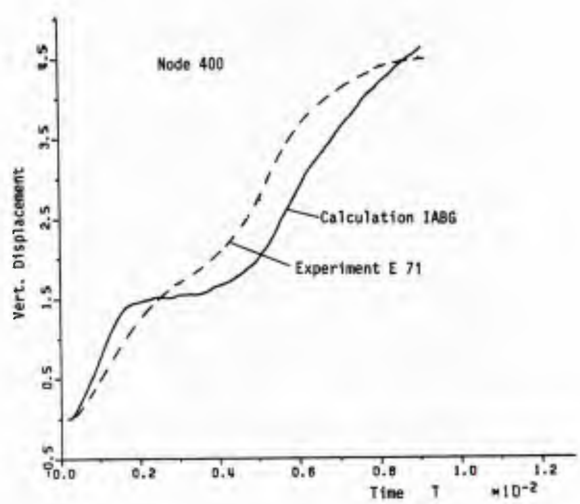

Fig. 4 Vertical displacement of the test bucket, comparison of calculation and experiment [1]

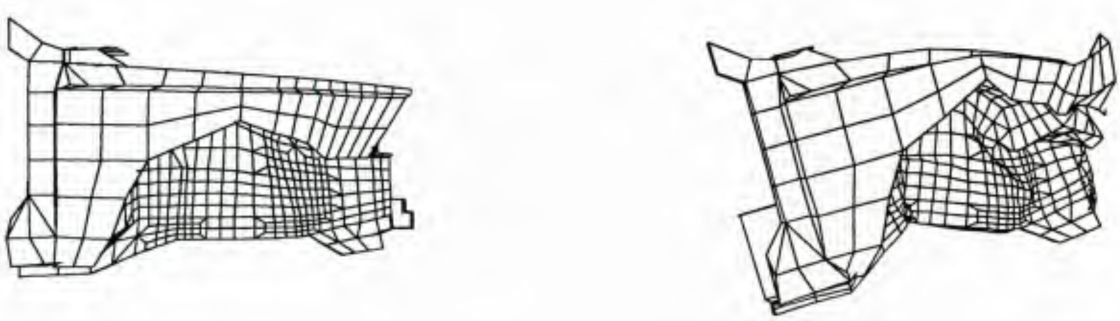

Fig. 5 Drop test with a front part of a car, undeformed and deformed structure

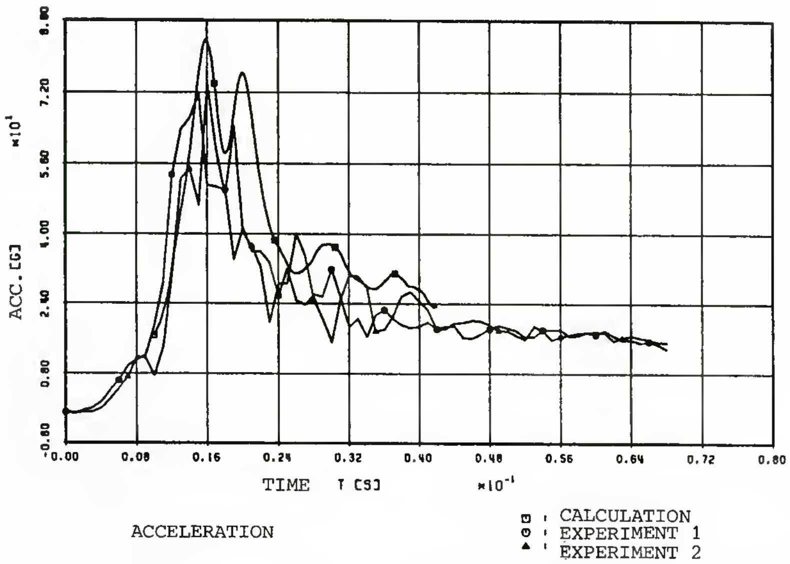

Fig. 6 Accelerations rear of the structure, comparison of calculation and experiment

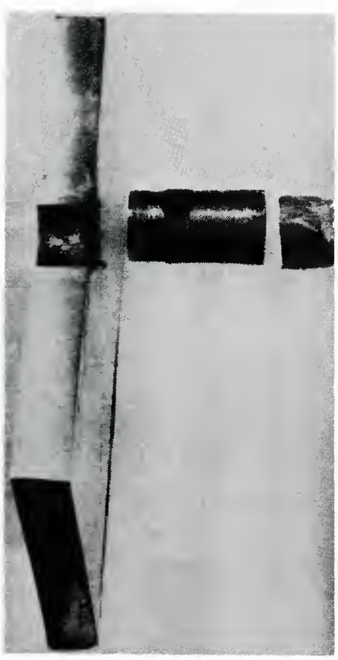

Fig. 7 Target plate with recovered projectile and plug [2]

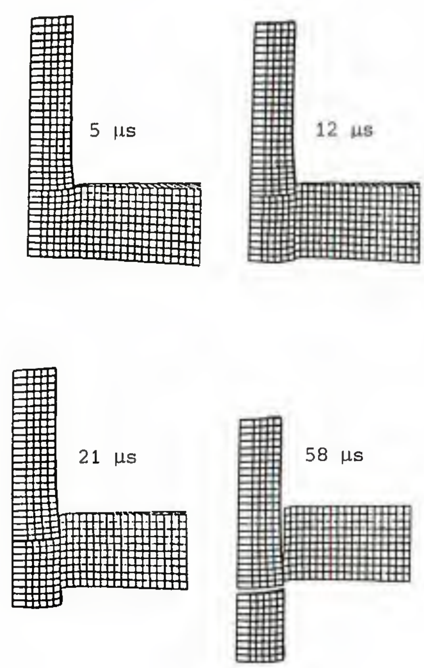

Fig. 8 Numerical simulation of the penetration process [2]

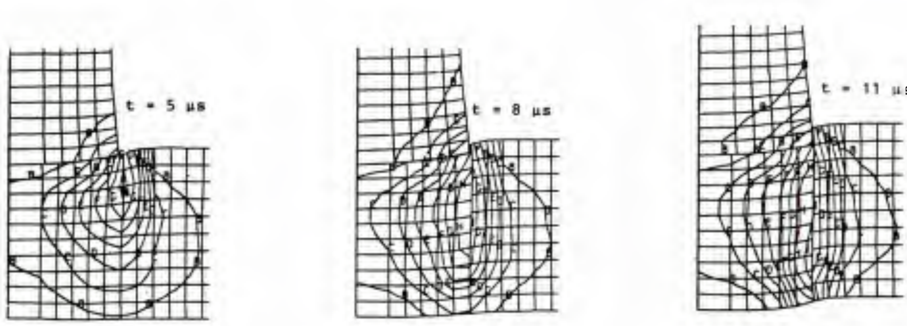

Fig. 9 Shear strain distribution during plug separation [2]

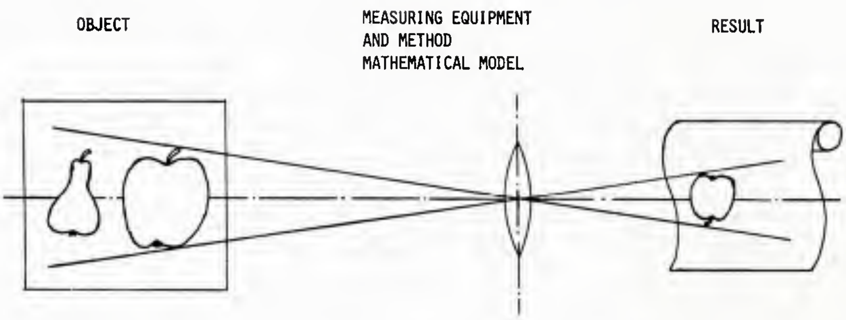

Fig. 10 Best case to be achieved

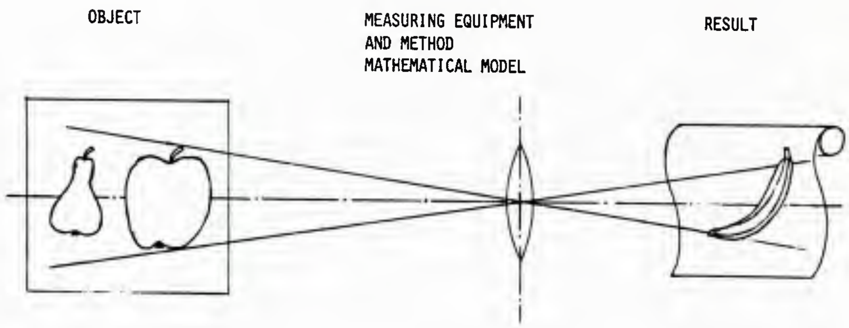

Fig. 11 Worse case

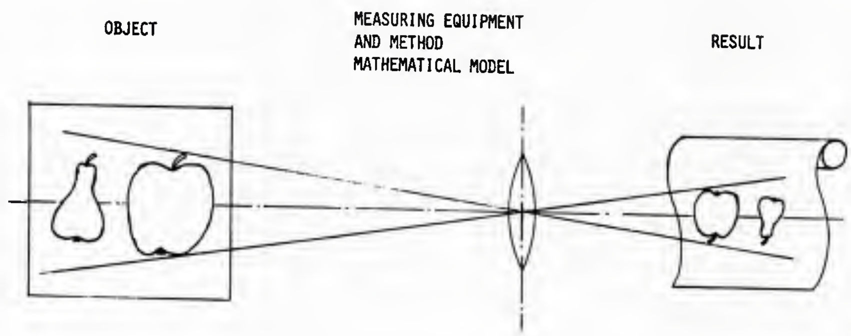

Fig. 12 Worst case

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14. Abstract

As part of its 61st Meeting the Structures and Materials Panel considered whether or not it should set up an activity to examine the possibilities of Structural Qualification by using Finite Element Analytical Methods in place of testing.

As a preliminary to its discussions it heard the two papers printed here. The first of these looks in general terms at the capabilities of existing organisations and systems vis-a-vis the standards which must necessarily be established before FEM qualification procedures can be implemented. The second paper looks in rather more detail at how non-linear FEM may be applied in support of structural tests.

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